FROM THE CHIEF SCIENTIST'S DESK

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In this issue of *NHMFL Reports*, scientists at Los Alamos National Laboratory (S.A. Crooker, D.G. Rickel, A.V. Balatsky, and D.L. Smith) investigate the phenomena of magnetic random noise arising from the fluctuation of the spin. Employing the fluctuation-dissipation theorem, they used the noise spectrum to study the response of the spin orientation to a space and time varying magnetic field B(r, t). Using a linearly polarized laser which is detuned from any atomic absorption, they studied the noise spectrum in rubidium and potassium vapors.

Random magnetization fluctuations along the z axis impart small polarization (Faraday) rotation fluctuations on the laser. Applying a small transverse field B, all magnetization fluctuation precess about B. The detuned laser ensures a perturbation free probe of equilibrium spin noise, wherein the atoms are not optically pumped or excited in any way. The ensemble exhibits zero net magnetization, with equal population of spins within ground state sublevels.

Measuring Random Spin Fluctuations for Perturbation-Free Probes of Spin Dynamics and Magnetic Resonance

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Noise in experimental measurements is historically and generally disregarded as being an unwelcome background, or at best, a nuisance to be minimized. Certain types of noise, however, contain a wealth of information about the system itself—a classic example being the small, inherent fluctuations of electrical current (current shot noise), which both demonstrates the discrete nature of the current carriers, and also directly yields the electron charge. In magnetic systems, fundamental noise can exist in the form of random spin fluctuations. In his seminal 1946 paper on nuclear induction, Felix Bloch noted that random, statistical fluctuations of N paramagnetic spins should generate measurable noise of order $\sqrt{N}$ spins, even in zero magnetic field.[1,2] By the fluctuation-dissipation theorem, this "spin noise" alone contains detailed information about the spin system itself. (The fluctuation-dissipation theorem states that the response of a system to an external perturbation—*i.e.*, the susceptibility—can be described by its spectrum of fluctuations while in thermal equilibrium.)[3]

In this work,[4] we address precisely these same $\sqrt{N}$ spin fluctuations, using optical techniques to passively and sensitively "listen" to the magnetization noise in a classical equilibrium ensemble of paramagnetic alkali atoms. These random fluctuations generate spontaneous spin coherences, which precess and decay with the same characteristic energy and time scales as the macroscopic magnetization of an intentionally polarized or driven ensemble. Correlation spectra of the measured spin noise reveals the complete magnetic structure of the atomic $^2S_{1/2}$ ground state (g-factors, nuclear spin, isotope abundance ratios, hyperfine splittings, nuclear moments, and spin coherence lifetimes) without having to excite, optically pump, or otherwise drive the system away from thermal equilibrium. Historically, this information is obtained with conventional magnetic resonance techniques (optical pumping and/or radio-frequency excitation), which necessarily perturb the spin ensemble away from thermal equilibrium. These noise signatures scale inversely with interaction volume, suggesting routes towards non-perturbative, sourceless magnetic resonance of small systems.

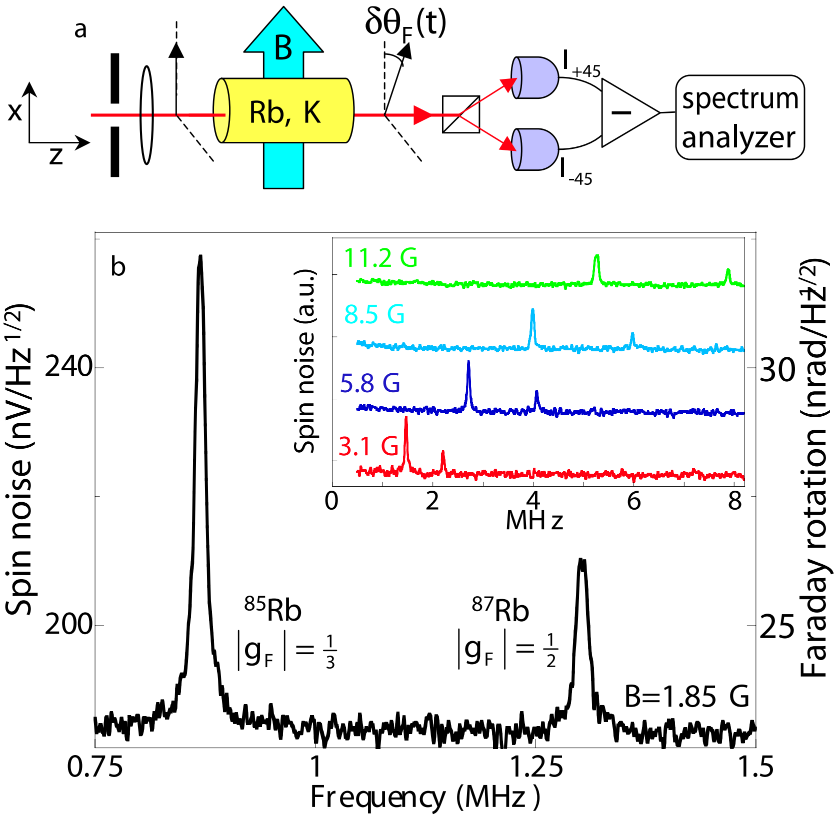

Figure 1. (a) Experimental schematic. Stochastic ground-state spin fluctuations $\delta M_z(t)$ impart polarization fluctuations $\delta\theta_F(t)$ on the detuned probe laser. **(b)** Measured spectrum of spin (Faraday rotation) noise in Rb vapor at T=369 K and B=1.85 G, showing spontaneous spin coherence peaks from ^{85}Rb and ^{87}Rb. The laser is detuned 25 GHz from the D1 transition (~794.8 nm), ensuring negligible absorption. Inset: The ^{85}Rb and ^{87}Rb spin noise peaks vs. magnetic field. Plots offset vertically for clarity.

A typical noise spectrum from rubidium vapor is shown in Fig. 1b. The sharp peaks at frequencies Ω=869 and 1303 kHz are due to random spin fluctuations that are precessing in the small 1.85 G transverse magnetic field, effectively generating spontaneous spin coherences between ground-state Zeeman sublevels. These coherences precess with g-factors $g=h\Omega/\mu_B B\sim 1/3$ and 1/2, which are the ground-state g-factors of the stable isotopes ^{85}Rb and ^{87}Rb. Coupling of the nuclear spin I to the $J=½$ valence electron splits the $^2S_{1/2}$ atomic ground state into two hyperfine levels with total spin $F=I\pm J$ and g-factor $|g_F|\cong g_J/(2I+1)$, where $g_J\cong 2$ is the free electron g-factor. Thus, the nuclear spin of ^{85}Rb ($I=5/2$) and ^{87}Rb ($I=3/2$) may be directly measured from spin fluctuations in thermal equilibrium. The 13 kHz measured width of these noise peaks indicates an effective transverse spin dephasing time ~100 μs. The spectral density of the spin noise is small—the ^{87}Rb peak in Fig. 1b contributes only 3.1 nrad/$\sqrt{Hz}$ of Faraday rotation noise above the photon shot noise floor of 23 nrad/$\sqrt{Hz}$. Because spin noise arises, effectively, from N uncorrelated precessing spins, the integrated area under the noise peaks should scale with $\sqrt{N}$. This is conveniently confirmed by noting that the integrated spin noise of the ^{85}Rb and ^{87}Rb peaks is 24.7 and 15.4 μV respectively, whose

Fig. 1a shows an experimental schematic. The linearly polarized laser, detuned from any atomic absorption, is focused through a cell containing rubidium or potassium vapor. Random magnetization fluctuations along **z** impart small polarization (Faraday) rotation fluctuations $\delta\theta_F(t)$ on the laser, which are sensitively measured with a balanced photodiode bridge. Helmholtz coils provide a small transverse magnetic field B along **x**, about which all magnetization fluctuations δM_z must precess. The detuned laser ensures a perturbation-free probe of equilibrium spin noise, wherein the atoms are not optically pumped or excited in any way. The ensemble exhibits zero net magnetization ($\langle M_z(t)\rangle=0$), with nominally equal population of spins within ground state sublevels. The spin noise correlation function, $S(t)=\langle M_z(0)M_z(t)\rangle$, has a Fourier transform $S(\omega)$ that is related simply to the power spectrum of $\delta\theta_F(t)$.

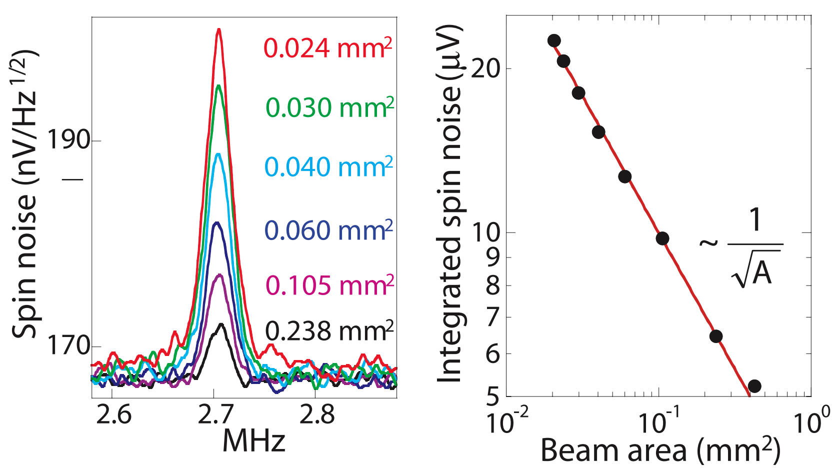

Figure 2. *Increasing* absolute spin noise with *decreasing* cross-sectional beam area. The spin density is fixed, with constant 145 μW laser power, and B=5.8 G. The integrated spin noise vs. beam area scales as $1/\sqrt{A}$.

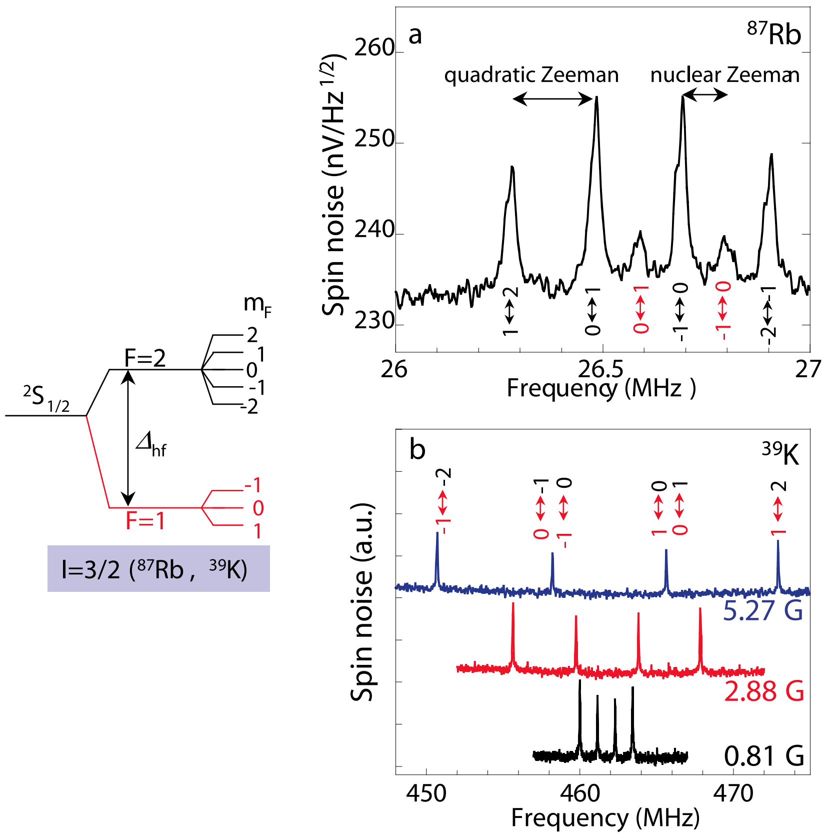

Figure 3. The ground-state hyperfine and Zeeman levels of ^{87}Rb (Δ_{hf} =6835 MHz) and ^{39}K (Δ_{hf} =461.7 MHz) which both have nuclear spin I=3/2. **(a)** Spin noise spectrum of ^{87}Rb at 38.1 G. Spontaneous coherences between all allowed ΔF=0, $\Delta m_F \pm 1$ Zeeman levels are resolved, from which hyperfine splitting and nuclear magnetic moment may be inferred. Coherences within the F=1 ground-state hyperfine level are labeled in red (refer to diagram). **(b)** *Inter*-hyperfine spin noise coherences (ΔF=1, Δm_F=±1) in ^{39}K at B=0.81, 2.88, and 5.27 G. T=456 K, and laser detuning is 220 GHz.

ratio—1.60—agrees quite well with the *square root* of the ^{85}Rb:^{87}Rb natural abundance ratio ($\sqrt{72.2\%/27.8\%}$=1.61).

In addition to scaling with $\sqrt{N}$, the measured spin noise actually *increases* when the diameter of the probe laser *shrinks,* as shown in Fig. 2. This result may be understood by considering that the Faraday rotation imposed on light passing through an intentionally-magnetized system is independent of beam area, so that the effective measurement sensitivity (rotation angle per unit polarized spin, θ_F/N) is larger for narrower beams. Therefore, fluctuations of order $\sqrt{N}$ spins induce correspondingly more signal. These data suggest the utility of noise spectroscopy for passive probes of small systems, where the absolute amplitude of measured fluctuations actually increases when probe size is reduced, as long as measurement sensitivity increases correspondingly. In magnetometry this situation can be realized, for example, through the use of smaller Hall bar magnetometers (since the Hall voltage is independent of area, for fixed current), or as is often the case for magneto-optical measurements, through a tighter focus.

Fig. 3 shows that spin fluctuations reveal detailed information about complex magnetic ground states arising from, *e.g.*, nuclear magnetism and hyperfine interactions. Fig. 3 shows the spin noise spectrum in ^{87}Rb at 38 G, where the single peak has split into six resolvable noise coherences, due to the effects of hyperfine coupling and nuclear magnetic moment. These peaks correspond to spontaneous coherence between the six allowed ΔF=0,Δm_F=±1 transitions. Lastly, spin fluctuations in thermal equilibrium also generate spontaneous spin coherence between *inter-hyperfine* Zeeman levels (ΔF=1,Δm_F=±1), as shown in Fig. 3b for ^{39}K. At low fields, these high-frequency noise coherences split away from the ^{39}K hyperfine frequency (Δ_{hf} = 461.7 MHz) with energy $h\Omega \cong \pm g_F \mu_B B$ and $\pm 3 g_F \mu_B B$, providing additional means of measuring Δ_{hf} from spin fluctuations alone.

We emphasize that these measurable ground-state spin coherences arise solely from random fluctuations while in thermal equilibrium, decidedly in contrast with normal methods for magnetic resonance. Nonetheless, the same detailed spectroscopic information is revealed, in accord with the fluctuation-dissipation theorem. The non-perturbative nature and inverse scaling of absolute noise with probe size portends favorably for local noise spectroscopy of small solid-state systems, where the planar geometry of many technologically-relevant structures is well-suited to high-spatial resolution studies. For example, in a semiconductor two-dimensional electron gas with electron density 10^{11}cm^{-2}, only ~1000 electrons are probed in a focused 1 micron laser spot. Thus, electron spin fluctuations (relative to the signal from a polarized system) are of order one part in $\sqrt{1000}$, as compared with only one part in $\sim\sqrt{10^9}$ in these studies.

[1] F. Bloch, *Phys. Rev*., **70**, 460 (1946).
[2] T. Sleator, *et al*., *Phys. Rev. Lett*, **55**, 1742 (1985).
[3] R. Kubo, *Rep. Prog. Phys*., **29**, 255 (1966).
[4] S.A. Crooker, *et al*., *Nature,* **431**, 49 (2004).